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RELIGION AND SCIENCE IN THE ATOMIC AGE[1]

KIRTLEY F. MATHER[2]

My friends among the nuclear physicists are by no means unanimous concerning the date when mankind entered the atomic age. Some of them place this milestone in history as of December 2, 1942; others give July 16, 1945 as the date. It was in December, 1942, that the first nuclear reactor developed a self-sustaining chain reaction of nuclear fission in the uranium pile that had been assembled in a former squash court on Stagg Field at the University of Chicago. It was in July, 1945, that the first atomic bomb was exploded on the testing grounds near Alamogordo, New Mexico. Regardless of the date chosen, enough time has elapsed since then and sufficient progress has been made in the application of this newly available form of energy to human activities so that it is now possible to see quite clearly what life in the atomic age may mean to mankind. Obviously, the new conditions of this new age affect not only the physical aspects of our daily lives, but also the attitudes of mind and heart, so important in the personal decisions we are called upon to make.

Although the atomic age seems to have burst upon us with explosive suddenness as well as violence, the fact is that it is a gradual development from that which went before. Each of the events to which I have referred proved to be a most impressive demonstration of the validity of the method of scientific research and of the ability of the countless individuals who had been engaged in that kind of intellectual activity throughout many generations. Even more important, they provided overwhelmingly convincing evidence in support of a new, fundamental concept concerning the nature of the world, that had been gradually developing in the minds of many physical scientists.

The idea that matter and energy were interchangeable realities in the physical universe was little more than a brilliant flash of highly imaginative insight during the first decade of the present century, when Einstein first proposed his epoch-making formula, $E = mc^2$. In the last thirty years, the nuclear physicists who are attempting to discover the secrets of atomic structure have definitely reached the conclusion that the fundamental "particles" which are the essential ingredients of matter are also units of energy. At the present time, matter is being transformed into energy every day in hundreds of laboratory experiments and scores of nuclear reactors. Ideas concerning the conservation of matter have undergone drastic change. Matter, today, is necessarily conceived as a local and temporary expression of energy.

The decline of materialism in science has been paralleled by the abandonment of the classical mechanistic concepts that stemmed from Newtonian physics.

[1] A summary based upon the Charles Felix Burke Lecture, delivered in Swazey Chapel, Denison University, April 15, 1957.

[2] Professor, Emeritus, of Geology, Harvard University.

Mechanical models are inadequate to demonstrate certain important aspects of current knowledge concerning atomic structure and sub-atomic operations. Mathematical equations and formulae, many of them based on non-Euclidean geometry, are now necessary. Operational principles are at the heart of much of the current scientific research. Physicists must deal with "disturbances in a continuum" rather than with discrete particles. Some of them even refer to electrons and other nucleons as "a series of singularities haunting space". The meaning of such a description is by no means clear, but it is a far departure from the mechanistic concepts concerning the nature of the universe that used to be so popular. Some of the data even seem to indicate that an electron can appear in one place and a microsecond later appear in another place, without any evidence whatsoever of having traversed the finite but very tiny distance between the two places. One is reminded of the angels that Thomas Aquinus used to dream about, occupying the head of a needle without bopping each other in the process.

Certainly the relationship between the physical sciences and religion is quite different today from what it used to be. Physics cannot and almost certainly never will validate religious ideas, doctrines or concepts; but physics today provides a much more fertile ground in which spiritual ideas and ideals may be cultivated than ever before.

Men of religion should give careful consideration to certain concepts which have arisen in recent years as a result of the success with which men of science have been exploring the universe. Knowledge about the nature of the world and of man reveals a marvelous orderliness. The mathematical order of the elements, the mathematical structure of the molecules, the innumerable regularities of nature, all call for explanation. It would appear that there must be some kind of administration of the universe. "The administration of the universe" is a perfectly valid, scientific label. Like most scientific labels, it is intended to reveal a small amount of knowledge and conceal a much larger amount of ignorance. The term simply indicates that there is something which determines order in the universe.

If we examine that something from a strictly scientific point of view, trying to be as objective as human beings can be, we discover that the administration of the universe has the characteristics of an organizing principle. Electrons, protons and neutrons are organized into atoms; atoms are organized into molecules; some of the molecules are organized into crystals; and some of the crystals are organized into the rocks of the earth's outer crust. Some of the molecules are organized into cells; some of the cells are organized into the bodies of multicellular plants and animals; and some of the individual plants and animals are organized into associated groups, such as colonies of corals, schools of fish, and herds of cattle. Some of the associated groups are organized into societies in which the necessity for mutual aid develops social consciousness, and some of the societies display a tendency to become organized into communities. It would now appear that there is available from the knowledge about the world and man, gained through physical and biological research, a suitable foundation on which to build a super-structure of spiritual concepts and religious doctrines that will have intellectual respectability.

Again, progress in science and of scientists in recent years has led to a very wide-spread acceptance of the inescapable fact that knowledge and mystery exist side by side. The farther we extend the horizon of the known, the more apparent it is that the universe and man are fundamentally mysterious. It is common practice nowadays for a man of science to say to his colleagues who can appreciate the meaning of what he says, "I do not understand what I know" about this or that. The fundamental mysteries pertaining to the nature of light, the "spin" of the nucleons, and the quantum-dynamics of energy levels, for example, are at least as mysterious to those well-versed in higher mathematics as to those who do not understand that language. It is not surprising, therefore, that in modern scientific circles there is characteristically much less of dogmatism and much more of humility than there used to be.

This more humble attitude of the scientist is often revealed in such statements as this: "In the atomic age, the real problems are not in the area of physics and chemistry; they are in the area of human relationships". The method of solving problems in physics and chemistry has been firmly established. Not yet, however, have we even developed a satisfactorily effective method for solving the problems of human relationships.

It is in this area of human relationships, if anywhere, that we find a lasting link between science and religion. It is here that value judgments play an inescapable role. Goals and purposes are as significant as body-build and physical environment. The spirit of man becomes the dominant factor. The scientist is really saying that beyond the limits of scientific knowledge there is spiritual knowledge that must be sought.

Fortunately in these same years during which mankind has been entering into the atomic age there has been great progress in religion and of men of religion. Thanks to the widening spread and deepening hold of scientific habits of minds the universe is no longer something to be feared, but now is something to be understood, even by men of religion. This means, among other things, that new concepts concerning the nature of the universe and the nature and destiny of man are to be welcomed rather than repelled. It means also that there is a clearer understanding of the basic distinction between the two kinds of knowledge, both of which are essential to human welfare.

One kind of knowledge is perhaps best designated as scientific knowledge. It is knowledge *about* the world and man. It is knowledge about material entities whose weight and dimensions can be precisely ascertained. It is knowledge about the measurable transformations of matter and of energy, knowledge about the motions of ponderable, tangible entities whose movements in space and time can be related to points on a scale.

The other kind of knowledge is, I think, appropriately called spiritual knowledge. It is knowledge *of* the world and *of* man. It deals with non-metrical realities, with intangibles that have no measureable relationships to space or time. It is, however, knowledge of that which is very real. We know it to be real, simply and solely because of what it does in human lives. Because it is knowledge of that which is the very antithesis of matter, we do well to call it spiritual knowledge.

Let me illustrate what I mean by this kind of knowledge. The artist may be

told a great many facts about a painting, whether it is on canvas or on cardboard, whether it is the result of the use of oil paints or crayons, whether it is of the surrealist, the neocubist or whatever other school of art. He may even be told about the artist who is responsible for the painting, whether he is a well-known expert or the merest tyro. But the artist will refuse to pass judgment upon that painting or picture until he has actually seen it with his own eyes, until he has discovered whether the picture causes something to well up from his inner depths, something of satisfaction and joy which causes him to say "Ah, it is beautiful!" or something of repellence and disappointment which causes him to say "No, that is something quite ugly." He must have knowledge *of* the picture before he will pass judgment upon it.

Or again, a poem about "the beauty of the sunset and the glory of the dawn" may alert the hearer or the reader to a possible experience which might be his. But it is not until the individual stands at sunset or at sunrise on some suitable vantage-point in open-minded contemplation that he has knowledge of the experience which does something to him so significant and so deep that he is at a loss for words with which to tell anybody else about it. "Knowledge of" is subjective, personal, private. "Knowledge about" is objective; it is in the public domain.

Spiritual knowledge involves the apprehension of aesthetic, moral, and ethical standards, principles, or values. It deals with the qualitative factors in human nature and in the universe, as distinct from the quantitative. The descriptive terms used in discussing this kind of knowledge are quality words, like lovely or ugly, inspiring or debasing, noble or sordid, righteous or evil, rather than quantity words, like millimeter or mile, gram or ton, micro-second or day. Its concepts can never be expressed in terms of metrical equations. Yet its relevance to human behavior is inescapable. Men may not always live in accordance with its finest principles, but their lives are always influenced to some extent by its concepts. Obviously we need both knowledge *about* the world and man and knowledge *of* the world and man.

Religion, like science, may be considered as a dynamic, self-correcting discipline. Those who enter such a discipline should seek general laws and concepts. Much of the data they will use are found in personal experiences, their own and those of others. They will also be concerned with the overt behavior, influenced or alleged to be influenced by such experiences.

The array of such data is vast and confusing. Many interpretations of experiences are recounted as though they were the facts themselves. Contradictory interpretations are at least as numerous as those which harmonize with each other. How can one intelligently screen out the trash and the error from the valuable and the true? Or, more basically, in these days of psychoanalysis, how can one have confidence at all in any spiritual interpretations of human experience, even in one's own?

There is, fortunately, a parallel between the methods to be used by those who would apprehend the spiritual aspects of the universe and of man, on the one hand, and by those who seek knowledge about the physical nature of the uni-

verse and man, on the other. Only those experiences are valid whose meaning can be ordered in terms of a system of spiritual values. In the search for understanding of the spiritual aspects of life, it is necessary to seek general laws connecting a number of facts of human experience, even as it is essential in scientific research to construct logical theories which explain relationships between a number of particular facts of human observation.

In religion, as in science, it is possible to keep one's mind open to new insights and at the same time to hold fervent convictions. How to do so is almost as great a problem for scientists in their discussions amongst each other as it is for men of religion in their attempts to inspire men and women to higher motives and commitments to nobler ideals. Tensions are bound to arise between one's doubts and one's convictions. Such tensions, however, are catalytic agents which should stimulate one's mind and strengthen one's character.

As we view the world around us in these early years of the atomic age, we are certainly ready now to say that it is not a question of *either* science *or* religion, *either* scientific knowledge and understanding *or* spiritual knowledge and understanding. Both kinds of knowledge and understanding are positively essential to the well-being of mankind.

SCIENCE AND THEORY[1]

JOHN A. BARLOW[2]

The wise explorer makes a map. As an integrated summary of observations, a map helps him to remember and to interpret what he sees. A theory is, in a sense, a type of map.[3] It integrates observations into a pattern and thus aids memory; it clarifies relationships.

As a result of the process of clarification, both maps and theories may serve a further function: that of anticipating or predicting further observations. From a good summary of the observations of an explorer as presented by a map of the specific paths he has covered, it is very often possible to make an estimate of what adjacent areas will look like. By making use of several such individual maps, it is possible to sketch in a tentative estimate of the geography of areas which have never been observed. Such estimates, if carefully prepared, are of tremendous value to the explorer now entering such an unexplored area. He does not know for sure what he will find, but he has something to go on. The same applies to prediction from a theory.

The first function of a theory, then, is to integrate previous observations and serve as a type of mnemonic device; it helps us to remember. Secondly, theory clarifies relationships and thus provides fruitful anticipations of the results of other observations; it helps us to predict (3, p. 98–99).

When we say that a theory helps us to predict, we mean that the theory has implications beyond the observations it was invented to integrate. These predictions do not necessarily concern the future. The predictive implications may concern future events, they may concern past events which no other theory has yet integrated, or they may concern areas already covered by other theories.

Sometimes the predictions of a theory are not verified, i.e., we find that the theory has implications which are not confirmed by observation. This indicates the limitations of the theory but does not destroy its usefulness. The theory is not of any value in ordering the contradictory information. However, if we drop the whole theory we shall have not just the contrary observations at loose ends, but all of the facts previously integrated by the theory (1, p. 67).

The situation is quite similar to that which obtains with simple mnemonic

[1] This paper grew out of conversations with Donald K. Adams of the Psychology Department at Duke University. The author appreciates the comments and criticisms of the manuscript in its formative stages made by Kenneth B. Marshall, Maylon H. Hepp and Parker E. Lichtenstein, of the Denison University faculty. Submitted for publication March 9, 1957.

[2] Assistant Professor of Psychology, Denison University.

[3] It is shown later in the discussion that while maps and theories serve some of the same functions, in modern science theory is not regarded as a replica of reality in the same sense that a map may be a replica of the geography of an area.

devices. The sentence "Blacky Brown runs over your grass but Violet Gray won't" is useful in helping one to memorize the color code in electricity:

Black	0	Green	5
Brown	1	Blue	6
Red	2	Violet	7
Orange	3	Gray	8
Yellow	4	White	9

A second example is the little verse for remembering the first letters of the cranial nerves: "On old Olympia's towering top a Finn and German viewed a hop."

If a new color were introduced which was to stand for the number ten, or if a thirteenth cranial nerve were identified, students would still find the sentence "Blacky Brown . . ." just as useful as ever in memorizing the colors for zero to nine and "On old Olympia's . . ." in memorizing the first twelve cranial nerves. They would continue to use these older devices until someone invented new ones or modified the old ones so that the new color or nerve could be memorized along with the rest.

A theoretical system is never "false" if it is useful to us in ordering knowledge. Rather theories go "out of date" as do automobiles, when more efficient models are developed (9, p. 117). In the case of gravitation Newton's theory replaced Aristotle's because it was more "true" in the sense that it was more useful in integrating the observations that were available concerning the positions and movements of heavenly bodies and tying in this information to other knowledge. Einstein's theory has replaced Newton's in the same way. We need not be surprised if even Einstein's theory is eventually replaced.

If we are to be practical, old models may still be useful for some purposes. On mountain trails, the very "out of date" transportation by horse is more satisfactory than the newest Buick. Ptolemy's theory in astronomy with the earth at the center is used today in navigation because it is more efficient for this purpose than the modern theory stemming from the work of Copernicus.

FAITH, FACT, AND THEORY

Systematization of knowledge may be achieved by subsuming the mass of information under as few propositions as possible. These propositions must synthesize the information so that it can be deduced from them. It is in this way that a theory aids memory. If one can remember the basic propositions then one does not need to remember the individual bits of information. We shall call such propositions "integrating assertions."

Hypotheses, assumptions, postulates, axioms, and basic tenets are some of the names given to various integrating assertions. The following table presents a classification of assertions according to the types of belief on which they are based.

Type of Assertion	Criterion	Characteristic of
Faith	**Intrinsically Unverifiable**	**Rationalism, Scholasticism**

Fact	Empirically Verified	Simple Positivism
Generalized Fact	Intersubjectively Verifiable	Empiricism
Theory	Useful	Logical Empiricism

Faith. An assertion of *faith* is a statement of belief which is intrinsically unverifiable (4, p. 166) but is intuitively acceptable as "true". Common examples are: the existence of God, the existence of the physical world, and the belief that men have some measure of free will. At one time the statements that, "A straight line is the shortest distance between two points" and that, "The earth is the center of the universe" were common beliefs taken on faith.

Negative assertions may be just as much assertions of faith as positive assertions. The atheist's assertion that "There is no God" and the agnostic's assertion that "We never know" are assertions of faith. Assertions of faith are assertions of absolutes and have no place in modern science.

Historically science has not always kept too far from being, in effect, a new religion. From the religious scholars of the Middle Ages the early scientists got their faith in God and in an orderly universe in which everything could eventually be explained. Their basic terms such as "matter," "cause," "natural law" were regarded as absolute entities not as convenient concepts (5, p. 278).

When Copernicus's *De Revolutionibus Orbium Coelestium* (Concerning the Revolution of the Heavenly Bodies) was published in 1543, it was presented as an hypothetical system convenient for certain calculations. This was a precaution of the editor, not a lack of faith by Copernicus in his system or any early anticipation of modern scientific sophistication. Copernicus himself is said to have died before he read the publication of his work and never knew of the "treachery" of the editor.

The Copernican system was taken as a handy hypothetical system and was taught in the schools along with the older Ptolemaic system. There were those who felt that the theory was not quite proper even though useful, but neither Catholics nor Protestants officially tried to prevent the schools from teaching it (7, p. 230).

In 1599, however, Giordano Bruno was burned at the stake for teaching quite bluntly that the Copernican system was the *true* system. Our respect for a great man, and a brave one, need not be lessened by noting that he was teaching a new faith, not science as distinct from faith.

Galileo's *De Revolutionibus* was put on the index in 1616 for repeating some of Bruno's heresy. In 1620 it was officially published again as a result of a few changes ordered by the Church. The changes amounted to stating that the book presented a convenient hypothesis rather than an account of reality. Thereafter Galileo was accepted by Church and Pope until he was interpreted as again attacking the Faith, whereupon he was put under a sort of house arrest for the rest of his life.

In effect, these bits of history relate the story of a battle between faiths, not science vs. faith. Johann Kepler finally won the battle for the Copernican theory and most people today believe in it with as much faith as their ancestors had in the Ptolemaic theory.

So far as modern science is concerned, neither of these theories is false. In fact, both continue to be useful and used, but for different purposes. Neither, on the other hand, does modern science regard the present formulations as necessarily the last answer.

Fact. An assertion of *fact* is a statement of belief that has been verified. This would appear to be the bed-rock type of assertion until we consider that the existence even of the physical world, and extent to which we can trust our senses or instruments, requires belief either as faith or opinion before we can accept the evidence of verification. Those who say that "Science must be true because it deals only with facts" do not know very much about the basis of science or the nature of scientific fact (9, p. 32).

Galileo may be used to mark a turning point on this issue. In one place he says that "It is impossible that a sense experience should be in conflict with truth," but later he says that "Sense must be accompanied by reason" and "Again in appearances, in which all agree, we make headway with reason, either to confirm the reality of that experience or discover its fallacy" (7, p. 221).

The study of Psychology in the areas of Sensation and Perception—especially those studies of individual sensory differences and defects, illusions and the effects of accidental or deliberate suggestion—should help to prevent anyone from too much confidence in the human sense organs. One of the simplest and most dramatic examples is the varied account of the "facts" reported by eye-witnesses to an accident or robbery.

The nature of the "facts" is also dependent on factors such as other beliefs. Facts depend upon the "frame of reference" or point of view of the observer or verifier as exemplified by the following quotation:

> The hasty will, of course, deny that it is a "fact" that the celestial sphere revolves once daily round the earth. We must admit that the "sphere" or "vault" is not a fact, but the revolution of the stars *is*. If anyone deny it, he must equally deny that a cricket ball thrown "straight up" does travel in a straight line and not in a curve. To which he will probably reply that "of course, it travels in a straight line relative to the earth, but to anyone fixed in space its path would be a curve." Well, the Greeks *were* on the earth and *not* fixed in space, so we come back to what we started with, namely, that it is a fact that the stars revolve round the earth!
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> ---
>
> Note that "facts" are no longer "true" when the conditions of their observation are changed. That is what Protagoras was hinting at and what Einstein has abundantly proved. There are, as far as we can see, no "absolute" facts but only relative ones. . . . Wightman, W. P. D. (9, p. 32)

More than this, directly verified facts are often personal. You may know as a fact, as something that you have verified for yourself, that you had a headache yesterday, or that you saw Sally Peters. There is no possible way, though, that I can directly verify that you had a headache. I may verify items such as that you say you had a headache, or that you looked as if you had a headache when I saw you. In the case of Sally: (a) I may have observed you with Sally; (b) you may have appeared to me to be talking to Sally; and, (c) you may tell me that you certainly saw her. Still the actual facts that I have available are these three

and not that you saw her. What you feel or see, etc., is directly verifiable only by you.

Assertions of "simple" as opposed to "generalized" facts are of a lower level than mnemonic devices. They have no properties at all of integration, clarification, or prediction. As isolated entities they soon become impossible to remember as they increase in number.

Generalized Fact. "Fact" may be included in intersubjective science only as "generalized fact", having been verified, or being open to verification, by more than one individual, and having the possibility of personal verification by the individual accepting it as a fact.

In an age of specialization, we apply the *warrant of authority* for most facts, i.e., we do not test each item ourselves but accept or reject fact to the extent that we accept the competence of the person or persons presenting the report. For all of us, most of what we call "facts" are really opinions based on authority or matters taken on faith in the authority. We accept the description of others because it is useful to do so and impossible not to do so in the face of the millions of facts we cannot test for ourselves.

We are dependent on authorities for our "facts" not only in the areas we call science, but in every aspect of our lives. We cannot avoid this but we can be aware of it. We can take things "with a grain of salt", checking for ourselves on the facts when it is possible and checking on the competence of the authorities whose word we accept and on the extent of agreement among authorities. As Whitehead (6, p. 302) puts it:

> Never swallow anything whole. . . . We live perforce by half-truths and get along fairly well as long as we do not mistake them for whole-truths, but when we do so mistake them, they raise the devil with us.

Theory. An assertion of *theory* is a statement of tentative belief which is in accord with the available evidence and accounts for or explains the evidence, but is held subject to further direct or indirect verification (see "opinion" 4, p. 166). Assertions of opinion in the form of theory are the backbone and basis of modern science.

If science is to be self-corrective, to constantly modify its theories so that they will contain and integrate more and more knowledge, it must take great care never to "block the way of inquiry." This requires that science hold all its assertions as opinions; all positions must be regarded as fallible and subject to change —never as permanent and infallible.

Charles Peirce discusses several "obstacles to scientific inquiry" that science needs to avoid (2, p. 41–3):

1. That any assertion is absolutely certain.
2. That some things can never be known.
3. That some things are unexplicable or unintelligible—are basic and ultimate.
4. That a given assertion or theory has received its final, perfect formulation.
5. That science should in any way be subservient to some non-scientific body.

The basic postulates and assumptions of religion are assertions of faith. The basic postulates of science *within the framework of science* are assertions of opinion. A person, scientist or non-scientist, may take the basic postulates of science on faith. If he takes the postulates of science on faith, they are then a portion of his personal religion. There is little basis for conflict between religion and science itself. However, there can be, and there is, conflict between science as a religion and other systems of religion.

Distinction between assertions of faith, opinion, and fact (and whether the fact is one of personal verification) is essential to clear and rational thought. Too often, opinion tends to be regarded as personally verified fact; too frequently, long established opinion tends to become faith. In the same way theories come to be regarded as empirical knowledge, or on the other hand become, in effect, matters of religion. This has resulted in much confusion and needless controversy between those who identify themselves with theology and science.

The important thing is not that we as scientists or laymen try to start without faith or fact assertions (this would be ridiculous), but that we recognize them as such. Scientists, seers, skeptics: none are lacking in some measure of personal faith, all have personal experience which to them individually is verified fact. The personal experience of the mystic in, say, talking to God is certainly a fact to him; the confidence of the scientist that his work is of some ultimate importance is basically a matter of faith.

Science is no less useful because it claims no certainty. It is its very lack of absolute assertion and its goal of agreement among investigators rather than absolute truth that is its strength. It is this that makes it flexible, useful to men of varying faiths, ever increasing the amount of knowledge it integrates, ever increasing the accuracy of its guesses concerning the future.

INTER-RELATIONSHIP OF THEORY AND RESEARCH

Theory and research are interdependent. This interdependence is especially evident in the *hypothetico-deductive method.* Previous observations are integrated by the formulation of hypotheses to account for them. Implications of the hypotheses other than the observations on which they were based are clarified. These predictions are verified by experimental test. The result of the test is that there are now new observations which are either explained by the hypotheses[4] (*i.e.*, are implied by the hypotheses) or indicate the limitations of the hypotheses.

The table (next page) outlines the steps in the hypothetico-deductive method and their relationship to the main sections of an experimental report.

Integration. We integrate by making a synthesis, by formulating assertions from which the material to be integrated can be deduced. The result of such integration is that the material is easier to comprehend and to remember—is plainer —has been explained. As there are always many different sets of assertions which

[4] When hypotheses have withstood numerous tests they are sometimes called laws. The term theory is generally reserved for an overall systematization of a number of laws and/or hypotheses.

can integrate a given body of data or set of observations, we set up certain pragmatic or practical standards. The usefulness of an hypothesis or theory (and thus, for science, its "truth") is dependent on such factors as:

1. That it require as few underlying assumptions as possible.
2. That its implications other than the information on which it was based be verifiable.
3. That it be compatible with other contemporary hypotheses, laws and theories.
4. That it be as acceptable as possible to those who will use it, introducing few unfamiliar ideas or concepts.

Section of Experimental Report	Step in Hypo.-ded. Method	Type of Logic	Result	Truth Value
Introduction	Integration	Abduction	Explanation	Pragmatic[5]
	Clarification	Deduction	Logical Analysis	Absolute
Procedure and results	Verification	Induction	Generalization	Probable
Discussion	Re-integration	Abduction	Explanation	Pragmatic
	Further Clarification	Deduction	Logical Analysis	Absolute

The formulation of a theory, or set of integrating assertions, is as much a creative endeavor as any work in art, literature or music. The explanation provided by a theory to a very great extent is a matter not only of presenting assertions which will "account for" the material but which will make the material more comprehendible and acceptable ("plainer"). The process resembles most, perhaps, the translating of literature from a foreign language into our native tongue (1. p. 84).

The type of logic used in integration is rarely named in discussions of scientific method. Charles Peirce, one of the early modern writers on scientific method and the originator of many modern ideas about science, called this type of logic "abduction."

Abduction may be illustrated by the following example. Say that a professor has just presented a class project involving the use of a bag of marbles. After class several marbles are found on the floor. A possible hypothesis which would integrate these observations is that the marbles found after class were dropped by the professor. Put in the form of a syllogism:

All the objects in the bag were marbles.
The objects on the floor are marbles.
Abduction: The objects on the floor came from the bag.

Clarification. We clarify by analyzing implications. *If* this is true *then* what follows? By deduction we explore the implications of assertions, we determine

[5] The "explanation" achieved through abductive reasoning has no necessary truth value at all and as such. It is considered "true" to the extent that it is useful in integrating other statements.

all that they really say. Valid deduction never introduces anything new (though it may appear new to us), but rather makes us aware of what was already there. For instance:

All the objects in the bag were marbles.
The objects on the floor came from the bag.
Deduction: The objects on the floor are marbles.

In this case the conclusion does not introduce anything not actually said in the first two statements. It merely repeats something already said but repeats it in a different way so that it is more apparent.

The conclusion of a deduction is logically proved by the deduction and is absolutely true *providing the assertions from which it is deduced are true.* This is the only place in science that the terms "proof" and "absolute" are appropriate. However, a deductive sequence must *start* from assertions of faith, fact, or opinion. The "absolute" and the "proof" of deduction are always: *IF* this, *then* that follows.

Verification. We verify by making some type of test, generally by performing an experiment. The result of the test is that we have new data, new observations, an empirical demonstration of the matter under concern. As soon as we go beyond simple description of what we observe—if we say, for instance, that the same thing would happen if we repeated the test—we are using the type of logic called induction and our conclusion is a matter of probability. For example:

The marbles on the floor are white.
The marbles on the floor came from the bag.
Induction: All of the marbles in the bag are white.

The more marbles that are taken from the bag in a random fashion and are found to be white, the more probable that all of the marbles in the bag are white (the field of statistics in mathematics is concerned in great part with telling us how probable such and such a thing is on the basis of what we have observed—assuming that the observations are accurate and that certain statistical assumptions are appropriate).

The most important distinction in our discussion of integration, clarification, and verification is that between the truth value of the different types of logic involved. We integrate by *abduction* and our only certainty is that the result *could be true.* We clarify by *deduction* and are certain that the conclusion *is true if* the assertions it starts from are true. We verify and are certain as a result of the test that the generalization we formulate by *induction is true* at least *some of the time.*

SUMMARY

The formulation of theories is one of the central tasks in science. Through theories we put our knowledge in order and make it more comprehensible. It is also through theories that we add to our knowledge. As we test implications of a theory concerning material other than that on which it was based, we discover

new knowledge—sometimes new observations, sometimes that two theories may be combined, sometimes that previously unexplained facts may now be accounted for.

A theory is not "true" or "false," it is more or less useful, more or less adequate, than some other theory or no theory at all. Theories are high level opinions, in the last analysis held always subject to future modification. As opinions they can never give us the certainty that we gain from personal faith or the near-certainty of personally verified fact. This is both their weakness and their strength.

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SECONDARY MOTIVATION THROUGH CLASSICAL CONDITIONING: BASIC EXPERIMENTAL DESIGN AND PROCEDURE[1]

JOHN A. BARLOW[2]

Precise test of the implications of theories, clear formulation of the issues, and development of new theoretical formulations, all often depend upon the development of new experimental techniques.

Hull (8), in his original theory, gives no place to pure classical or respondent conditioning as such. In his system reinforcement, defined as tension reduction, is involved in all learning. This position is slightly modified in Hull's (9) last revision, primarily as a result of the work of Mowrer (10). On the other hand Guthrie (7) centers his entire system on a single postulate that all learning is basically a matter of classical conditioning. Estes' (6) more recent formulation is similar to that of Guthrie. Tolman (13) does not entirely endorse Guthrie's positiou, but several of his various types of learning presuppose the occurrence of a form of classical conditioning. Though there is some doubt as to their success in demonstrating classical conditioning, the so-called latent learning studies were intended to show the inadequacy of a tension-reduction theory.

It is the intention of the present paper to present an experimental design which permits the demonstration and investigation of pure respondent or classical conditioning and what is also "latent learning" (if a long tradition may be broken and the term not restricted to maze learning but used to refer to learning not manifest in immediate performance but evidenced by modification in future performance as a function of the learning sequence).

The following design is based primarily on the insights and point of view expressed in Adams' (1) "Restatement of the problem of learning" (even down to his prediction that a single trial would be sufficient to demonstrate conditioning in appropriate circumstances). From Zener's (14) work we gained confidence that some such design would be fruitful and that the traditional point of view on classical conditioning as a matter of simple response transfer is inadequate and misleading.

The first experimental study using this procedure is now being revised (2, 4) and a theoretical paper based on the work has been previously published (3).

[1] Current work using this technique is being conducted using funds provided by the National Science Foundation and the Denison Research Foundation. The initial work in this area started at Oberlin College under the direction of Dr. John Finan. The design was formulated as a portion of a dissertation submitted to the Graduate School of Arts and Sciences, Duke University, in partial fulfillment of the requirement for the Ph.D. degree. Submitted for publication June 13, 1957.

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EXPERIMENTAL DESIGN

Preliminary Conditions

Subjects. Male albino rats 100 to 130 days old.

Living Conditions. For one week previous to the first experimental period and during the experiment each S lives in an individual cage with water and food available at all times. The normal daily fluctuations in illumination through the windows of the Animal Room are not controlled but all electric light circuits are disconnected.

Preliminary Handling. During the preliminary week each S is lifted out of his cage by the tail and transferred for a few moments to another cage once a day. Then the S is again lifted by the tail and transferred back to his home cage.

Apparatus. A plywood box with internal dimensions $9\frac{1}{2} \times 3\frac{1}{2} \times 10$ inches, front of glass, and floor consisting of a grill through which alternating current shock may be administered. A 15 watt conventional light bulb two feet below the floor grill shines through a frosted glass plate six inches below the floor, furnishing the illumination to be varied as a conditioned stimulus or "signal". An Argon Glow Lamp (Westinghouse and G. E. type S 14, $2\frac{1}{2}$ watts, 105–125 volts, Model AR-1) one inch outside the front glass furnishes a constant source of illumination. Illumination of timing devices and of observer's records are also furnished by Argon Lamps.

Electric Shock. The floor grill consists of six #7 copper bus bars running lengthwise through the apparatus. The shock is administered through a resistance circuit connected to 117 VAC. The front floor bar is connected to the ground side of the line; the rear bar to the hot side through 60 K. The following pairs of bars are connected together: 2 to 5, 3 to 6, 4 to 7; 15 K resistors are placed between bars 1 and 2, 3 and 4, 5 and 6, 7 and 8. The bars are arranged in two sets of four bars with $\frac{1}{2}$ inch between the sets of bars and the front and back of the box and each other and $\frac{1}{4}$ inch between the centers of the bars in each set. This arrangement results in a fairly uniform shock regardless of the position of the rat and a single piece of feces can not short out the circuit. The shock administered by this circuit typically results in the S making a sort of "dancing" response; squeals or violent jumping about rarely occur.

Training Day

Experimental Period. Each S is placed in the apparatus for one ten-minute period.

Stimulus-to-be-conditioned or "signal". In order to control for any original properties of the electric light stimulus used, two procedures are followed for each experimental-test sequence. For half of the S's the occurrence of the light serves as the conditioned stimulus or "signal"; for the other half of the S's the light is "on" when an S is put into the apparatus on training day and its termination serves as the "signal".

Electric shock. The shock occurs for a ten second period and can not be terminated by the S.

Training Trial. Each S receives one "trial" or conditioning sequence. This conditioning sequence occurs after the S has been in the box five minutes—or approximately one-half of the training period.

Test Day

Experimental period. Each S is placed in the apparatus for a period of forty minutes approximately twenty hours after training. At this time the box contains a metal bar running lengthwise through the center of the box 3¼ inches above the floor. This bar and the floor grill are connected to a vacuum tube circuit (designed by Pilgrim, (12)). Any connection formed between the bar and the floor grill results in a change in bias of the vacuum tube. This tube, in turn, controls several relays which provide the desired effects and records.

Lighting. There are two test procedures. (1) The training signal ("light" or "darkness") occurs for half of the S's in each training group whenever and for however long the S touches the metal bar with any of its extremities (the vacuum tube circuit is arranged so that contact with the hairy portion of the body will not activate the circuit). (2) For the other half of the S's in each training group, the training signal is present when the S is put into the apparatus. For these S's contact with the bar terminates the signal.

Records. Time spent by the S touching the "Response Bar"; number of contacts with the bar; running qualitative account of the S's behavior, especially on training day.

PROCEDURE

The electric clock and the counter which record the duration and number of the S's responses are enclosed in a sound-proofed box. The sound of the room ventilation exhaust system provides a screening noise in the experimental room.

The experimental room is kept in darkness except for the sources of illumination specified in the "experimental design". The experimenter observes the S from a distance of approximately four feet.

The S's are inserted into the apparatus from the top through a trough-shaped wooden funnel which is removed and replaced by the box lid as soon as the S is inside (the S's are handled by the tail in all phases of the experiment). On test day the vacuum tube circuit is not turned on until after the S has been inserted. Thus touching the bar while being put into the apparatus does not activate the "signal" circuits (the signal circuits take approximately ten seconds to warm up and only after this period does touching the bar record as a response or change the level of illumination).

Before an S is put in, any feces are removed and the apparatus wiped out with a cloth dampened in a mild Lysol solution. This prevents any accumulation of smell of urine or feces in the apparatus, and gives the experimental situation a distinctive odor.

SUMMARY OF SUBGROUP BREAKDOWN

During Test, Bar Contact Results in	Conditioned Stimulus or "Training Signal"	
	A. Light Occurring	B. Light Terminating
I. Light Occurring	Subgroup IA	Subgroup IB
II. Light Terminating	Subgroup IIA	Subgroup IIB

"Neutral" Conditioned Stimulus

By having the occurrence of light the training signal for half of the S's (Group A) and its termination the training signal for the other half (Group B), we provide what is for all of the S's taken together a statistically neutral stimulus (i.e., any initial properties of the light are cancelled out for the two groups combined). A similar procedure has been used by Mowrer and Lamoreaux (11), and by Dinsmoor (5).

Balanced Test Conditions

During the test period the light is not present for half of the S's when they are introduced into the apparatus and bar contact by the S results in occurrence of the light (Group I); for the other half of the S's the light is present when they are introduced into the apparatus, in this instance bar contact by the S terminates the light for the duration of contact (Group II).

"Neutral" Response

For half of the S's contact with the response bar results in occurrence of the level of illumination which was their training signal (Subgroups IA and IIB); for the other half of the S's such contact results in the termination of the signal used in their training (Subgroups IB and IIA). In terms of a record of amount of time during test spent *in presence of the training signal*, the result for the four subgroups combined will average fifty per-cent of the length of the test period if the training signal has no secondary properties as a function of the conditioning sequence (and thus the amount of time touching the bar is the same for Subgroups IA and IIB as it is for Subgroups IB and IIA). Any significant increase or decrease from this theoretical fifty per-cent (or any trend during the test period which differs significantly from the straight line of fifty per-cent) may be judged the result of acquired or conditioned properties of the signal if the rats were assigned randomly to the various subgroups. Thus if we define as our group response all behavior which keeps the signal present, it might be put that for the subgroups taken together we have a statistically neutral response (neither approach nor avoidance).

Using the above procedure, the effects of unlearned properties of the type of stimulus used as signal or of the motor response used as a learning index (as well as any interactions) may be parcelled out and their amount estimated by an analysis of variance. The obtained total group curve during test compared to the

theoretical fifty per-cent line gives an estimation of any acquired properties of the signal with these other factors controlled.

SUMMARY

New discoveries are often contingent upon the development of appropriate techniques. We have presented an experimental design and procedure now in use which involves application of principles found in the work of Adams (1) and Zener (14). This design permits the study of pure respondent or classical conditioning using a "latent learning" technique. The conditioning sequence involves only the association of the C.S. and the Unc. S. Change in the motivational or reinforcing properties of the C.S. for the S is then tested by making occurrence or termination of the C.S. dependent upon the frequency and duration of certain operant or motor responses of the S.

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NOTES ON THE DETERMINATION OF OXYGEN ISOTOPE RATIOS BY DENSITY MEASUREMENTS[1]

JOHN B. BROWN[2]

ABSTRACT

Oxygen isotope ratios have been determined using the water density method at temperatures from 5° to 8°C. The advantage which was gained in temperature control by working at these low temperatures was offset by a more sluggish response of the floats to density differences than had been previously observed by workers using water baths thermostated near room temperature. The overall accuracy for these conditions was about the same as that reported for experiments at 25°C.

INTRODUCTION AND APPLICATION OF THE METHOD

In addition to the direct method of mass spectrometry, the isotope ratio of oxygen may be determined by a measurement of some physical property of water which is dependent on the isotopic composition of the water. Chief of the properties which have been measured are the refractive index and the density.

Refractive index measurements for O^{18} studies have been little used in this country but have been rather widely used by Russian workers, particularly Brodsky.[3] These measurements are especially desirable when a complete isotopic analysis of the hydrogen and oxygen in the water is to be made.[4]

Dufour[5] is often credited with the origination of density determinations by the method of floating equilibrium, but earlier Davy had used the procedure to determine the density of sodium.[6] The method became a precise analytical tool in the hands of Richards and co-workers.[7] Their method consists in noting the precise temperature at which the unknown solution attains the same density as a previously calibrated float. Lamb and Lee proposed a magnetic float which

[1] Contribution from the Chemical Laboratory of Northwestern University. This material is taken in part from the dissertation presented by John B. Brown to the Graduate School of Northwestern University in partial fulfillment of the requirements for the degree of Doctor of Philosophy. The experimental work was performed at Northwestern University under the direction of and with the help of Dr. Malcolm Dole.

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[3] A. E. Brodsky *et al*, *Acta Physicochim. U. R. S. S.*, **7**, 611–620 (1937); A. E. Brodsky and O. C. Scarre, *ibid.*, **10**, 729–752 (1939); also S. G. Demidenko, *ibid.*, **13**, 305–311 (1940).

[4] G. N. Lewis and D. B. Luten, *J. Am. Chem. Soc.*, **55**, 5061–5062 (1933).

[5] M. L. Dufour, *Compt. rend.*, **84**, 1080 (1862).

[6] H. Davy, *Trans. Roy. Soc. (London)*, 21 (1808).

[7] T. W. Richards and J. W. Shipley, *J. Am. Chem. Soc.*, **34**, 599–603 (1912); **36**, 1–10 (1914); T. W. Richards and G. W. Harris, *ibid.*, **38**, 1000–1011 (1916).

has been used with success.[8, 9] Another method in which pressure is the variable was developed by Gilfillan and Polanyi[10] and has been used by several investigators.[11] The temperature-float was first applied to isotopic analysis of heavy water by Lewis and Macdonald.[12]

Professor Malcolm Dole suggested to the author that it would be advantageous to make density measurements in the temperature range between 5° and 8°C. on samples of water whose isotopic compositions were being investigated. Because the density of water changes only slightly with temperature in this range compared with the greater variation of density with temperature at room temperature, it would be much easier to control the temperature of the water bath to assure density variations of less than one part in 10,000,000.

This paper is concerned with some observations of float behavior when density determinations were made at this low temperature.

EXPERIMENTAL

The temperature-float method has been used by many investigators to determine the density of unknown waters, and the procedures are fairly standard. A float chamber containing the sample water and Pyrex float is immersed in a dual chamber thermostated water bath. Observations of movement of the float at any given temperature are made through a window in the insulation of the water bath. The temperature of zero float velocity is noted and compared with the flotation temperature of the float in a standard water. Density differences may be calculated from tables of water density as a function of temperature and the coefficient of expansion of the float.

For work at the temperatures used in this study, the water bath was fitted with cooling coils connected to a ⅕ h.p. Frigidaire compressor unit. Themostatically controlled knife-heaters supplied heat to offset the cooling from the refrigerating unit and to keep the bath at constant temperature. Over a period of time, this arrangement consistently maintained the temperature of the water bath constant to within 0.001°C.

The temperature of the inner bath was measured with the same platinum resistance thermometer and Mueller bridge used by previous workers in this laboratory.

All the floats used in this study were constructed from Pyrex brand glass tubing. For small quantities of sample water, micro-floats (1 or 2 mm. in diameter and about 10 mm. long) were made. The behavior of other floats of various sizes and shapes was observed during the determination of the coefficient of expan-

[8] A. B. Lamb and R. E. Lee, *J. Am. Chem. Soc.*, **35**, 1666–1693 (1913).

[9] N. F. Hall and T. O. Jones, *ibid.*, **58**, 1915–1919 (1936); N. F. Hall and O. R. Alexander, *ibid.*, **62**, 3455–3462 (1940).

[10] E. S. Gilfillan and M. Polanyi, *Z. physik. Chem.*, **A166**, 254–256 (1933).

[11] E. S. Gilfillan, Jr., *J. Am. Chem. Soc.*, **56**, 406–408 (1934); C. H. Greene and R. J. Voskuyl, *ibid.*, **56**, 1649 (1934); L. A. Webster, M. H. Wahl, and H. C. Urey, *J. Chem. Phys.*, **3**, 129 (1935); H. C. Urey, G. B. Pegram, and J. R. Huffman, *ibid.*, **4**, 623 (1936).

[12] G. N. Lewis and R. T. Macdonald, *ibid.*, **1**, 341–344 (1933).

sion of the floats. All the isotopic determinations were made with Float No. 3 (a slim, cylindrical micro-float) immersed in samples of water contained in a 10-mm. float chamber.

The water samples for isotopic analysis were prepared by combining deuterium-free hydrogen with oxygen over hot copper. The hydrogen was obtained by electrolysis of deuterium-free water which had been previously prepared by subjecting water to three stages of fractional electrolysis.[13] The water synthesis apparatus was also fitted with a bulb which was used to collect gaseous oxygen to be measured on the mass spectrometer.

Distilled water from the laboratory tap was used as a standard for each of the sample waters.

All water for density determinations was purified according to the vacuum distillation procedure developed by Roake.[14] Because the effect of dissolved air on the density of water is almost ten times as great at 7° as at 25°C., extreme caution was observed so that all samples were handled in the same manner and that the density was determined as soon as possible after breaking the vacuum in the distillation train.

Movement of the float within the float chamber was observed with a Gaertner M101AT Telemicroscope[15] mounted on a stand which permitted vertical and horizontal adjustment to bring the float within the field of view.

The determination of the temperature of floating equilibrium is often achieved by drawing the best straight line through a series of points of float rate plotted as a function of temperature. The flotation temperature is taken as that temperature at which this straight line crosses the zero float rate line.

However, it is possible to use an analytical method to determine the temperature of floating equilibrium once a linear relation is established between float velocity and departure from the flotation temperature. This eliminates the uncertainty in plotting points on a graph, in deciding on the best straight line between those points, and in reading off the flotation temperature. The analytical method also allows an estimate of the precision in the equilibrium temperature.

If Θ_i and v_i denote the temperature and the corresponding rate of displacement when the float is rising and if Θ_k and v_k are the same values when the float is descending, then it can easily be shown that the flotation temperature, Θ_0, (when $v = 0$) is given by

$$\Theta_{0,i,k} = \Theta_i + \frac{\Theta_k - \Theta_i}{|v_k| + |v_i|} |v_i| \tag{1}$$

The several $\Theta_{0,i,k}$'s, calculated from the observation of float rates at various temperatures, are averaged to obtain the mean $\bar{\Theta}_0$. This procedure was followed in obtaining all the flotation temperatures reported here.

Densities of water samples were determined by interpolation in Dorsey's ta-

[13] W. E. Roake, Ph.D. Dissertation, Northwestern Univ., 1948.

[14] W. E. Roake, *op. cit.*, pp. 18–21.

[15] Made by the Gaertner Scientific Corp., 1201 Wrightwood Ave., Chicago 14, Ill.

ble.[16] The difference in density between two samples of water is given by the following expression from Randall and Longtin:[17]

$$\Delta D = \{D_a(t_a) - D_a(t_b)\} - D_f(t_a)\alpha(t_b - t_a)$$

where D_a is the density of the standard water at the flotation temperatures, t_a for the standard water and t_b for the sample water; $D_f(t_a)$ is the density of the float at t_a, equal to $D_a(t_a)$; and α is the volume coefficient of expansion of the float. Since the density of water at the temperatures of this study differed by a small amount from unity, the above expression may be simplified without loss of accuracy to:

$$\Delta D = \{D_a(t_a) - D_a(t_b)\} - \alpha(t_b - t_a). \tag{2}$$

FLOAT BEHAVIOR DURING DENSITY DETERMINATIONS

A. Linearity of Float Velocity as a Function of Temperature

In the previous section, the relation between float velocity and departure from the equilibrium flotation temperature was assumed to be essentially linear. It is possible to show the degree of approximation in this linear relation between float rate and temperature as follows:[18]

(For the purposes of the following calculation, it will be assumed that the float is a sphere. When it is very near to equilibrium temperature it is subject to three forces: the downward force of gravity, the upward force due to the displaced liquid, and the retarding effect of viscosity which is given by Stokes' formula.)

If v is the rate of vertical displacement of the sphere, r is its radius, D^* is its density, and if D and η are, respectively, the density and viscosity of the medium, then the condition for equilibrium of forces is given by

$$6\pi\eta rv = 4/3\pi r^3(D - D^*)g$$

or

$$v = K(D^* - D)/\eta \tag{3}$$

where $K = -2/9\ gr^2$, a constant dependent on the dimensions of the float. The float is ascending when $D^* < D$ (positive v) and is descending when $D^* > D$.

At some new temperature $\Theta' > \Theta$,

$$\Delta = \Theta' - \Theta$$

$$D^{*\prime} = D^*(1 - A\Delta)$$

$$D' = D(1 - B\Delta)$$

[16] N. Ernest Dorsey, "Properties of Ordinary Water-Substance," Reinhold Publishing Corp., New York, 1940, Table 93, p. 200.

[17] M. Randall and B. Longtin, *Ind. Eng. Chem., Anal. Ed.*, **11**, 44–46 (1939).

[18] This treatment was suggested by that used by H. Perperot and F. Schacherl, *J. phys. radium*, **6**, 319–322 (1935).

and $$\eta' = \eta(1 - C\Delta)$$

where A, B, and C are the temperature coefficients of the density of the float and of the density and viscosity of the medium, respectively. The rate of displacement at this new temperature is given by

$$v' = K(D^{*\prime} - D')/\eta'$$

or

$$v' = (K/\eta)\{D^*(1 - A\Delta) - D(1 - B\Delta)\}/(1 - C\Delta). \tag{4}$$

If $C\Delta$ is small, then

$$1/(1 - C\Delta) \simeq 1 + C\Delta$$

o that Equation 4 becomes

$$v' = v - (K/\eta)\{D^*(A - C) - D(B - C)\}\Delta - (K/\eta)(D^*A - DB)C\Delta^2. \tag{5}$$

The temperature coefficient of density of the float, A, may be related to the volume expansivity of the float, α, through the defining relation for density

$$D^* = W/V$$

so that

$$A = \frac{dD^*}{d\Theta} = -\frac{W}{V}\left(\frac{1}{V}\frac{dV}{d\Theta}\right) = -D^*\alpha. \tag{6}$$

(Values of α, the thermal coefficient of volume expansion, for the floats used in this study were determined and are reported in another paper.[19])

For the floats used in this study, A has the approximate value of -9×10^{-6} g./ml./deg. Between 6° and 8°, the average change in the density of water, B, is -45×10^{-6} g./ml./deg. Between 6° and 8°, the viscosity of water decreases from 1.4728 to 1.3860 centipoise;[20] thus $C = -4 \times 10^{-4}$ poise per degree.

By substitution of these values into Equation 5, it can be seen that for $\Delta \simeq 0.1°$ (D^* and D are very nearly unity), the term in Δ^2 is of the order of magnitude of 10^{-10} and can be neglected in comparison with the term in Δ of magnitude 10^{-5}, and the rate of float displacement may be regarded as a linear function of temperature change near the equilibrium point.

B. Viscosity Effects

Some workers calculate the flotation temperature with the help of a graph of float velocity vs. departure from equilibrium temperature. Given an observed value of float velocity, the departure of the temperature of observation from the equilibrium temperature can be read from the graph. Usually two observations are made for a check. For such a procedure to be used it is necessary that the slope of this line (float velocity vs. temperature departure) be quite steep so as to minimize errors in reading temperatures from the graph.

In order to make a comparison of the experimental conditions of the present

[19] J. B. Brown, *J. Sci. Labs., Denison Univ.*, **44**, Art. 7 (1957).
[20] N. Ernest Dorsey, *op. cit.*, Table 84, p. 184.

procedure with previous work done at room temperature, data taken in the Northwestern laboratories by Glenn H. Jenks and by W. E. Roake were readily available. Jenks' operating conditions were such that the slope of the line he used was −1282.1 mm./min. per ohm (temperature measured in terms of resistance of the platinum thermometer) for a float which was in equilibrium with standard Lake Michigan water at 25.83°C.[21] The slope of the line for the float used by Roake was −540.3 mm./min. per ohm.[22] Roake's float was in equilibrium with standard water at 22.989°C. Both of these workers used a "micro" float about 3 mm. in diameter, a float chamber which had been made from 12-mm. Pyrex tubing, and samples of water up to 2.5 ml.

Observations of two "micro" floats (Float Nos. 2 and 3) made for the present study were carried out in similar float chambers with similar volumes of water. Density equilibrium for these two floats was in the 6–7° temperature range. The average slope ($dv/d\Delta$) for Float No. 2 in an 8-mm. float chamber was −27.5 mm./min. per ohm. Two observations were made with Float No. 2 in a 10-mm. float chamber. The average slope for these two observations was −40.1 mm./min. per ohm. For float No. 3, the average slope (45 determinations) was −37.7 mm./min. per ohm when a 10-mm. float chamber was used. These data are presented graphically in Figure 1.

The reason for this more sluggish response from the floats is obvious from Equation 3. The viscosity of water increases with decreasing temperature, so it should be expected that the floats move more slowly at temperatures near the point of maximum density of water than at room temperature. The fact which was not apparent at the start of this work was the magnitude of this viscosity effect.

C. Shape and Wall Effects

In the derivation of an expression for the velocity of the float (Equation 3) it was assumed that the float was a sphere and that Stokes' law was applicable. Partington states that Equation 3 holds only if vr is small compared with η.[23] The maximum velocity of any of the floats during any observation was of the order of 0.00167 cm./sec.; most were considerably less than 0.00067 cm./sec. The floats used for this study were of varying size, but the largest had a diameter of 9 mm. Thus, the maximum value of vr may be assumed less than 0.0008 cm.^{2}/sec. The viscosity of water at 8°C. is 0.01386 poise.[20] Since η is more than 17 times greater than the maximum value of vr, it is not unreasonable to expect Stokes' law to hold for the motion of a spherical float at temperatures very close to equilibrium. Andreasen has verified that Stokes' law is valid for non-spherical particles.[24]

A more general treatment of the subject would lead to

$$v = k(D^* - D)/\eta \qquad (7)$$

[21] G. H. Jenks, Ph.D. Dissertation, Northwestern Univ., 1945, p. 16.

[22] W. E. Roake, *op. cit.*, from graph following p. 15.

[23] J. R. Partington, "An Advanced Treatise on Physical Chemistry; Vol. II, The Properties of Liquids," Longmans, Green and Co., New York, 1951, p. 86.

[24] A. H. M. Andreasen, *Kolloid-Z.*, **48**, 175 (1929); cited by Partington, II, p. 87.

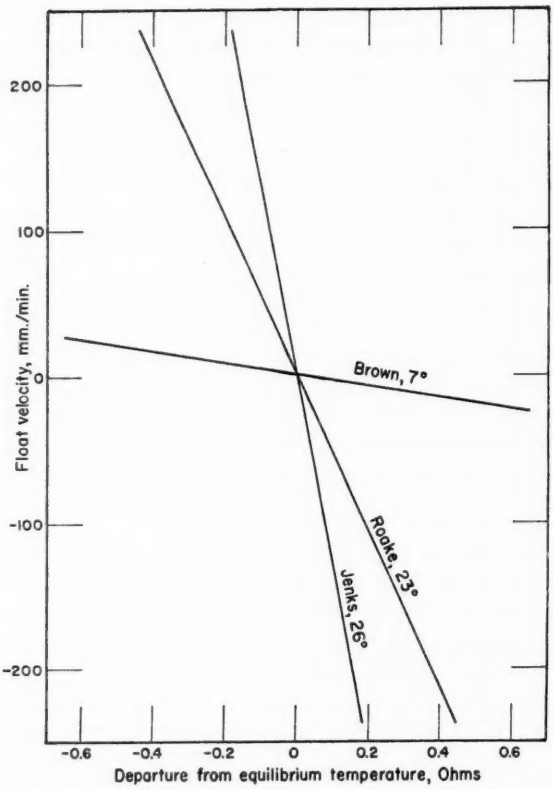

FIG. 1. Float velocity as a function of departure from equilibrium temperature for different temperatures.

"where k is a constant which depends on the space between the float and the wall of the tube, and seems to be proportional to the 5/2 power of this distance."[23]

For this study, it may be assumed that Equation 3 is valid, with the understanding that K is an empirical constant, the value of which depends on the size of the float, the shape of the float, and the size of the chamber in which the float is immersed.

Differentiation of Equation 4 yields

$$\frac{dv}{d\Delta} = K \frac{D_e}{\eta_e} \frac{(B - A)}{(1 - C\Delta)^2} \tag{8}$$

where the subscripts refer to the density and viscosity of of the water at the equilibrium temperature and Δ is the departure from this equilibrium temperature.

The K-values for the floats used in this research have been determined by

TABLE 1

Shape Factors for Floats

Float No.	Weight (grams)	No. of Obsvns.	Size of Float Chamber	$\frac{dv}{d\Delta}$ (mm./min. per deg.)	$K(1 - C\Delta)^{-2} \times 10^{-6}$
2	0.02971	8	8-mm.	−2.183	.0728
		2	10-mm.	−3.190	.1212
		2	18-mm.	−6.834	.2573
3	0.02761	45	10-mm.	−2.999	.1401
		2	18-mm.	−2.849	.2463
11	1.4687	2	18-mm.	−11.349	.4474
12	0.5915	2	18-mm.	−17.595	.4912
21A	0.7516	2	18-mm.	−24.001	.6271
21	0.7529	2	18-mm.	−14.343	.6252
22	0.6943	4	18-mm.	−6.912	.4568
31	0.5240	2	18-mm.	−17.557	.6163
26	0.8237	2	18-mm.	−24.554	.5579

plotting the float velocity against departure from equilibrium resistance (temperature). The slope of this line may be substituted into

$$K/(1 - C\Delta)^2 = (dv/d\Delta)(\eta_e/D_e)\{1/(B - A)\} \tag{9}$$

together with known constants to give a value for $K/(1 - C\Delta)^2$. This quantity is referred to as the "shape factor". These values for the various floats are summarized in Table 1. The units of K are such as to give a float velocity of mm. per minute when the departure from equilibrium temperature is expressed in degrees and the viscosity in centipoise and density in g./ml.

D. Precision of Observations

Because density measurements were made indirectly by observing temperature and reading density values from a table, constancy of temperature during an observation and precision of temperature measurement were of utmost importance to achieve good results. From the density tables, it is possible to calculate the temperature variation which corresponds to a change in water density of ±0.1 p.p.m. The results of such calculations are summarized in Figure 2.

The result of differentiating Equation 4 may be written

$$dv' = K/(1 - C\Delta)^2\{(D_e/\eta_e)(B - A)\, d\Theta.\} \tag{10}$$

Equation 10 will allow a calculation of the allowable variations in float velocity, dv, which are equivalent to a density change of ±0.1 p.p.m. Assumed values for $K/(1 - C\Delta)^2$, known values of D_e, η_e, B, and A and values of $d\Theta$ at a given temperature were used to calculate the values shown in Figure 3.

At relatively low temperatures, the larger values of $d\Theta$ will give a value of dv more favorable to the experiment than at higher temperatures. The viscosity of water has the opposite effect; as the temperature is increased, η decreases and the value of dv increases. The difference in the coefficients of density of the water and of the float, $(B - A)$ also causes dv to increase with temperature.

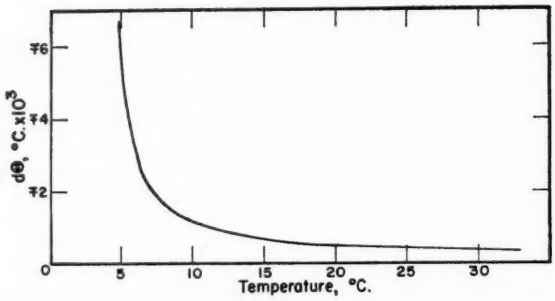

FIG. 2. Allowable variation of temperature, $d\Theta$, equivalent to a density change of ± 0.1 p.p.m. as a function of temperature. (The $\mp$ sign is assigned to $d\Theta$ because temperature must be decreased to increase density of water.)

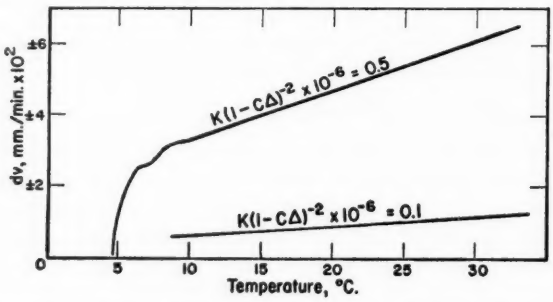

FIG. 3. Allowable variations in float velocity, dv, which are equivalent to a density change of ± 0.1 p.p.m. as a function of temperature. ($A = -10 \times 10^{-6}$ g./ml./deg.)

It would be desirable to obtain such operating conditions that would allow the maximum variation both of temperature and of float velocity. From an inspection of the graphs it would appear that no such operating temperature exists. For any advantage in temperature control gained by working at lower temperatures, there is a corresponding disadvantage in the observation of float velocity.

Another way of representing the interrelationships of variations of temperature and of float velocity is a plot of the product $d\Theta\, dv$ against temperature. Such a curve is shown in Figure 4. The ordinate is shown in relative units: the magnitude depends on the value of $K/(1 - C\Delta)^2$ for the float in question; the shape of the curve and the temperature of the maximum value are independent of this value. This graph indicates that there is an optimum temperature for the experimental work at 5.3°C. It happened that the floats used in this study were in density equilibrium with water at temperatures between 5.7° and 8.7°, temperatures which are not far removed from this optimum point.

There are two observations concerning the float behavior which may be noted. Randall and Longtin advocated use of the smallest possible float chamber which would give free clearance to the float.[17] They did find that the small clearance

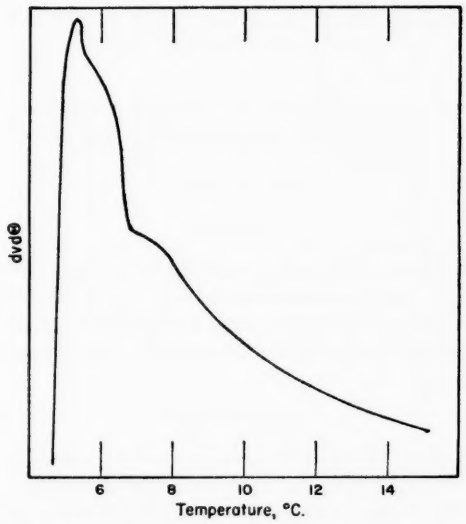

FIG. 4. Product of allowable variations of velocity and temperature, $dvd\Theta$, each equivalent to a density change of ± 0.1 p.p.m., as a function of temperature. (Ordinate in relative units.)

meant a more sluggish response of the float to density changes. The slopes of the velocity-temperature curves for Float No. 2 in an 8-mm. and in a 10-mm. chamber (Table 1), which were determined under identical conditions except float chamber size, support this observation. An increase in float chamber diameter of 2 mm. resulted in a 46 per cent increase in the slope of the velocity-temperature curve.

The other observation is concerned with the shape of the float. In their studies, Richards and co-workers advocated the use of a float shaped like a "very plump cigar."[7] Emeleus, *et al.* found that the most rapid and certain response to changes of temperature was obtained with a slim, cylindrical float,[25] although they present no data to show a quantitative comparison of various shapes. The data of Table 1 show that the slim, cylindrical float (No. 3) had a larger shape factor than did the bullet-shaped float (No. 2). From the preceding discussion concerning the effect of shape factors on precision of results, it would be expected that more precise results would be obtained with the slim, cylindrical float than with the bullet-shaped float when both are used under similar conditions in a 10-mm. float chamber.

ACKNOWLEDGMENTS

The author wishes to express his gratitude to the Air Force Cambridge Research Center for financial support during this work. He would also like to express his thanks to Dr. Malcolm Dole for direction and support in this research.

[25] H. J. Emeleus, *et al.*, *J. Chem. Soc.*, 1207 (1934).

COEFFICIENT OF EXPANSION OF PYREX GLASS FLOATS USED IN DENSITY DETERMINATIONS[1]

JOHN B. BROWN[2]

ABSTRACT

A direct measurement of the volume coefficient of thermal expansion of Pyrex glass floats used in density determinations was possible because of the temperature range employed. The coefficients of expansion vary from 9.0 to 10.2 $\times$ 10^{-6} per degree (in the range from 1.3° to 8.7°C.) and depend on the thermal history of the float.

INTRODUCTION

Various materials including Pyrex glass and fused quartz have been used for the construction of the floats used in density determinations by the method of floating equilibrium. Fused quartz is probably the ideal material because of the very small temperature coefficient of expansion of quartz. However, the fact that many investigations have been conducted with Pyrex glass is probably to be attributed to the relative ease of working with Pyrex glass compared with quartz. If the float is made from Pyrex glass, the observed data must be corrected for the expansion of the glass over the temperature interval involved.

If the density of the float were to be measured at two different temperatures, it would be possible to evaluate the change in specific volume from the density determinations. If the float were adjusted to be in density-equilibrium with water at a temperature between 5° and 8°, then it would also be in density-equilibrium with water at some temperature between 1° and 4°. From the known value of the density of water at these two temperatures, a direct calculation of the volume coefficient of expansion of the glass float could be made.

Most frequently, data are recorded in terms of the linear coefficient of expansion: the change in length per unit length which accompanies a change in temperature, $\lambda = (1/L)(dL/dT)$*. Less frequently, the cubic coefficient of expansion, or the change in volume per unit volume per degree, $\alpha = (1/V)(dV/dT)$ is recorded. It is the cubic coefficient that is used as the correction factor in calculating densities by the method of floating equilibrium. The value for the volume coefficient of expansion is three times the linear coefficient of expansion.

[1] Contribution from the Chemical Laboratory of Northwestern University. This material is taken in part from the dissertation presented by John B. Brown to the Graduate School of Northwestern University in partial fulfillment of the requirements for the degree of Doctor of Philosophy. The experimental work was performed at Northwestern University under the direction of and with the help of Dr. Malcolm Dole.

[2] Assistant Professor of Chemistry, Denison University.

* Coefficients of expansion are usually denoted by α. However, for this work λ has been used to denote the linear expansion coefficient and α is reserved for the cubic expansivity.

Over a reasonably short temperature range, the expansion of glass can be represented as a linear function of temperature:

$$(\Delta L/L)_T = A + BT. \tag{1}$$

The value of B in Equation 1 is the linear coefficient of expansion.[3] Over a greater temperature range, the expansion curve shows a convexity toward the temperature co-ordinate and higher powers of T must be used in an analytical expression for the expansion.

At higher temperatures, the expansion becomes much more complicated. Up to a certain temperature, dependent on composition, the expansion is nearly linear. Above this temperature, the expansion increases several fold. As the increasing temperature approaches the softening point, the rate of expansion decreases and above a certain temperature there is a contraction with increasing temperature.

The temperature at which the expansion curve indicates a change in the rate of expansion is called the "transformation point" by some workers and the "critical temperature" by others. The temperature at which the expansion curve changes to negative curvature is called the "softening point" or "upper annealing temperature."

The general form of the expansion curve discussed above is true for all glasses if the range of temperature is great enough and if the measurements are sensitive enough. The critical temperature and softening point are both general properties associated with glass. The temperature values associated with these points seem to be a function of the composition of the glass.

In the lower portion of the expansion curves referred to above, measurements of expansion per unit length at various temperatures are generally reproducible even when the glass sample is obviously inhomogeneous.[4] Very good agreement on expansion values usually means that the calculated linear coefficients of expansion for different samples of the same glass agree with each other within one per cent. However, a greater variation is not sufficient to reject a given batch in the manufacture of Pyrex brand glassware.[5]

It is generally known that the coefficient of expansion of a piece of annealed glass is less than that of a strained glass. In the lower temperature ranges, the expansion curve for a strained sample of glass lies above that of a sample of well annealed glass of the same composition. At some temperature below the critical temperature, the two curves cross and the thermal expansion of the strained glass is lower than that of the annealed glass. Turner and Winks[4] designate the point of intersection of the two curves as the divergence temperature, D_t. Apparently relief from the internal tension in the strained glass begins to occur at a certain temperature, dependent on the degree of strain. Relief from this tension causes a permanent contraction in length.

Turner and Winks found that this difference between expansion of strained

[3] J. B. Saunders and A. Q. Tool, *Bur. Standards J. Research*, **11**, 799–810 (1933).
[4] W. E. S. Turner and Francis Winks, *J. Soc. Glass Technol.*, **14**, 84–109 (1930).
[5] H. R. Lillie, Corning Glass Works, private communication, July 30, 1954.

and annealed glasses was shown by glasses containing boric oxide to a greater degree than for another glass composition.[4] There is evidence to indicate that this difference is not only dependent on composition but also on the previous thermal history of the glass sample. Saunders and Tool found that the mean linear expansivity between 20° and 200°C. of Pyrex glass could be changed as much as 10 per cent by subjecting the glass to heat treatments in the range from 450° to 750°C.[5]

To this date, the only explanations for this difference in expansion of strained and annealed glass have been on a qualitative basis in terms of a relief from internal tensions which was mentioned above. However powerful a tool X-rays are in explaining glass structure, the changes which occur during the annealing process of glass are too subtle to be detected by X-ray analysis.[6]

A summary of the published values of coefficients of expansion of Pyrex brand glass is given in the discussion section which follows.

EXPERIMENTAL PROCEDURE

The equipment used in this research was the fairly conventional equipment for determining densities by the method of floating equilibrium, except that the thermostated water bath was maintained at a temperature near the temperature of maximum density of water.

All floats used in this work were constructed from Pyrex brand glass tubing. A thin-walled tube 8–10 mm. in diameter was drawn from stock tubing. At one end of this section of tubing an eye was formed and a length of Pyrex rod was fused to the other end. (Figure 1 shows a typical float and a "micro-float" of the type used in the isotopic work.) The floats were so constructed that they slowly sank in water at room temperature. Because the floats were still warm when they were put into the water, the glass acquired a certain amount of temper during the construction of the float. Some of the floats were annealed in the oven of Northwestern Technological Institute glass blowing shop. The annealing temperature was approximately 550°C. Those floats which were not annealed have been designated as "tempered" floats.

The floats were then adjusted so as to be in density equilibrium with water at some temperature between 0° and 4°C. Because the annealing process caused a small contraction in volume of the float, the floats were adjusted to the proper density range after they were annealed.*

Some workers prefer to make an approximate adjustment in the density of the float by the addition of a small amount of mercury to the bulb before sealing.[7] The expansivity of such a float was determined during the course of this work.

In order to ascertain if there were any effect on the expansivity due to the internal pressure of the hollow floats, a "vacuum float" was constructed by evacu-

[6] B. E. Warren, *J. Am. Ceram. Soc.*, **17**, 251 (1934).

[7] I. Kirshenbaum, "Physical Properties and Analysis of Heavy Water," McGraw-Hill Book Co., New York, 1951, p. 266.

* The density of Float No. 21 changed from 0.9999 g./cm.^{3} before annealing to 1.0001 g./cm.^{3} after annealing.

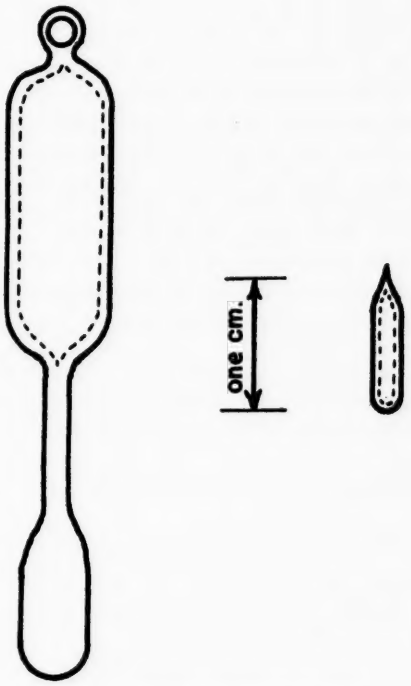

FIG. 1. Typical floats shown to scale

ating the Pyrex tube on a Welch Duo-Seal vacuum pump before sealing off the bulb.

Approximately 20 ml. of water were needed in the float chamber for the floats described above. For the isotoptic analyses of oxygen samples by density determinations, there was a practical limit of 2 or 3 ml. in the amount of water which could be made from the oxygen samples. For use in these small amounts of water, micro-floats were constructed by drawing down 8-mm. Pyrex tubing to a thin-walled capillary 1 or 2 mm. in diameter and sealing off a float about 10 mm. long.

Preliminary work with micro-floats indicated that the solubility of air in the water samples would affect the reproducibility of measurements of float velocity at any given temperature. To avoid this difficulty, it was decided that the expansivity measurements would be conducted in air-free water under its own vapor pressure ("saturated" water as opposed to "compressed" water).

The distilled water available in the laboratory was redistilled from alkaline permanganate. During this distillation, no attempt was made to protect the water from the atmosphere because subsequent treatment would remove the dissolved gases. A sufficient quantity of the redistilled water was introduced into a clean, dry float chamber which was then capped with a 19/38 standard

taper outer joint. A stopcock in this cap made it possible to seal the contents of the float chamber from the external atmosphere.

The dissolved gases in the water were removed by attaching the open float chamber to a water aspirator for about 20 minutes. For the first few minutes, the water "boiled" vigorously as the dissolved gases were removed. The de-gassed water was quickly frozen with a dry ice—acetone mixture and the float was introduced into the float chamber. The float chamber was recapped and evacuated on the vacuum pump for another 20 minutes. The stop-cock at the top of the float chamber was then closed; the float chamber disconnected from the vacuum pump; and the ice allowed to melt.

Thus, the float was immersed in pure, air-free water and sealed from contact with the atmosphere. The pressure within the float was that which was due to the vapor pressure of the water.

The temperature of floating equilibrium was determined by observation of the float velocity at different temperatures as described in a previous paper.[8] The density of air-free water at atmospheric pressure was interpolated from Dorsey's table.[9]

The values for the isothermal compressibility of water

$$\beta = -(1/V)(dV/dP)_T = (1/D)(dD/dP)_T \tag{2}$$

at one degree intervals between 0° and 10° were interpolated from Grassi's values.[10] Since the density of water in this temperature range is very close to unity, Equation 2 may be written

$$\Delta D = \beta \Delta P$$

or

$$\Delta D = -\beta(1 - P) \tag{3}$$

where P is the final pressure (the vapor pressure of water).

Substitution of the values of the vapor pressure of water[11] and values of β into Equation 3 gives the correction to be applied to the tabulated densities to obtain the density of air-free water at its own vapor pressure.

The volume expansivity is the change of volume per unit volume per degree of temperature change. By using the relation $V = W/D$, the volume expansivity can be related to a change of density:

$$\alpha = (1/V)(dV/dT) = -(1/D)(dD/dT). \tag{4}$$

[8] J. B. Brown, *J. Sci. Labs., Denison Univ.*, **44,** Art. 6 (1957).

[9] N. Ernest Dorsey, "Properties of Ordinary Water-Substance," Reinhold Publishing Corp., New York, 1940, Table 93, p. 200.

[10] C. Grassi, *Ann. chim. et phys.*, (3) **31,** 437–478 (1851), cited by Dorsey, p. 239. Grassi's values were chosen from the several in Dorsey because they are the only ones which indicate the variation of β with temperature at less than 10-degree intervals. Grassi's values at 0° and 10° agree quite closely with other values quoted by Dorsey.

[11] N. Ernest Dorsey, *op. cit.*, p. 560.

TABLE 1

Volume Thermal Coefficient of Expansion of Annealed Pyrex Floats

Float Number	Weight (grams)*	Floating Temperatures	Corrected Densities#	$(-\Delta D/\Delta T) \times 10^6$
11	1.4687	2.307 6.929	0.999 8995 .999 8575	9.0_9
11	(Repeat measurement) (Fresh water sample)	2.255 6.970	.999 8980 .999 8557	8.9_7
12	0.5915	1.367 7.930	.999 8657 .999 8056	9.1_6
12	(Repeat measurement) (Same water)	1.370 7.931	.999 8659 .999 8055	9.2_1
21A (Note)	0.7516	1.226 8.801	.999 8594 .999 7965	9.1_9
21A	(Repeat measurement) (Same water)	1.233 8.083	.999 8597 .999 7963	9.2_6

* The weight of the floats is a measure of their over-all volume; since the density of the floats is very close to unity, the weight in grams is numerically equal to the volume in cubic centimeters.

The corrected densities are the densities (g./cm.^{3}) of air-free normal water under the saturated vapor pressure at the temperature indicated.

Note.—Float No. 21 (see Table 2) was annealed and readjusted in weight before this measurement.

Since the densities in the working range of temperature are very close to unity, the relation

$$\alpha = -\Delta D/\Delta T \tag{5}$$

may be used to calculate the volume expansivity from density and temperature data.

EXPERIMENTAL RESULTS

Data obtained from expansivity measurements on the several Pyrex floats are reported in this section. Repeat measurements to verify the results were made in each case. Some of the repeat measurements were made after an interval of several days with a fresh sample of water in the float chamber; others were made with the same water without opening the float chamber to the atmosphere. Whether or not the repeat measurement was to be made with the same water or with a fresh sample of water was a matter of random chance.

A. Annealed Floats

Expansivity measurements were made on three floats which had been annealed prior to density adjustment. The results are given in Table 1.

TABLE 2

Volume Thermal Coefficient of Expansion of Tempered Pyrex Floats

Float Number	Description (Weight in grams)	Floating Temperatures	Corrected Densities	$(-\Delta D/\Delta T) \times 10^6$
21	Tempered (0.7529)	2.572 6.790	0.999 9063 .999 8635	10.1_5
21	Repeat measurement Same water	2.556 6.788	.999 9059 .999 8636	10.0_0
22	Tempered (0.6943)	3.144 6.127	.999 9160 .999 8885	9.2_2
22	Repeat measurement Fresh water sample	3.318 5.982	.999 9194 .999 8931	9.8_7
22	Repeat measurement Fresh water sample	3.158 6.113	.999 9174 .999 8890	9.6_1
22	Repeat measurement Fresh water sample	3.256 6.006	.999 9186 .999 8924	9.5_3
31	Hg-filled (0.5240)	2.051 7.268	.999 8916 .999 8415	9.6_0
31	Repeat measurement Fresh water sample	2.069 7.255	.999 8922 .999 8421	9.6_6
26	Evacuated (0.8237)	0.697 8.733	.999 8328 .999 7509	10.1_9
26	Repeat measurement Same water	0.703 8.733	.999 8332 .999 7509	10.2_5

B. Tempered Floats

The coefficients of expansion of two floats similar to those described above were determined immediately after fabrication. When the measurements on Float No. 21 were complete, it was annealed and redesignated Float No. 21A (data on this float appear in Table 1). Another float was a mercury-filled float—a globule of mercury was introduced into the float before it was sealed off. This mercury-filled float did not have the solid glass tail pictured in Figure 1. Still another float was evacuated with a Welch Duo-Seal vacuum pump before the bulb was sealed off. The results of these measurements are summarized in Table 2.

C. Aged Micro Floats

Two micro-floats for use with small samples of water were constructed. These floats were not annealed but approximately 18 months elapsed between the time of fabrication and the expansivity measurements. Between times of intermittent use in water density determinations these floats were stored in capped weighing bottles full of distilled water. The results of the expansivity determinations on these floats are given in Table 3.

TABLE 3

Volume Thermal Coefficient of Expansion of Aged Micro Pyrex Floats

Float Number	Weight (grams)	Floating Temperatures	Corrected Densities	$(-\Delta D/\Delta T) \times 10^6$
2	0.02971	2.295 7.070	0.999 8990 .999 8510	10.0_5
2	(Repeat measurement) (Same water)	2.293 7.061	.999 8989 .999 8515	9.9_4
3	0.02761	3.561 5.723	.999 9216 .999 9006	9.7_1
3	(Repeat measurement) (Same water)	3.582 5.702	.999 9218 .999 9011	9.7_6

DISCUSSION OF RESULTS

An inspection of the data in Tables 1, 2 and 3 shows (1) that there is a significant reduction in the coefficient of expansion upon annealing which is to be expected from the previous discussion, (2) that there is no significant difference between freshly-made large floats and the aged micro-floats, (3) that mercury-filled and evacuated floats were not significantly different from the others, and (4) the reproducibility of measurements for any given float was about $\pm 0.1 \times 10^{-6}$.

Previously published values for the expansion coefficient of Pyrex glass are summarized in Table 4.

Tables for internal use at the Corning Glass Works give 3.25×10^{-6} per degree C. for the nominal average linear coefficient of expansion between 0° and 300°C. for annealed samples of Pyrex glass, code number 7740. An attempt is made to hold within ± 0.05 of this value, but this is not a rejection value and the glass may occasionally depart as much as ± 0.10 from the nominal value.[5]

Except for that of Buffington and Latimer, the values cited in Table 4 are valid for a temperature range considerably above room temperature. The values of expansivity for this work were determined for a short temperature interval of about 5°C. The linear expansivity at room temperature is about $0.04_4 \times 10^{-6}$ per degree lower than the 0–300°C. coefficient.[5] Thus, 0.13×10^{-6} should be subtracted from the values of volume expansivity in Table 4 before making a critical comparison with the values determined in the present work.

The data of Tables 1, 2 and 3 are in substantial agreement with the values in Table 4. The differences could be due partly to differences in annealing and partly to composition control of the sample. It is believed that the slight variation from one float to another within each category measured is due to variations in composition. From this, it should be concluded that any precise work involving expansivity of glass would necessarily require a measurement on the actual piece of glass employed in the work.

It should also be noted that the method of measurement presented here is

TABLE 4

Expansion Coefficients of Pyrex Glass from Several Sources

Source	Glass*	Expan. Coef. × 10^6		Temperature Range, °C.
		Linear	Cubic	
International Critical Tables[12]	"Pyrex Laboratory"	3.2		19 to 350
Buffington & Latimer[13]	G702EJ	3.4		−24 to 25
Saunders & Tool[3]	"A Pyrex"	Note		25 to 200
Jones & Jalen[14]	"Pyrex"		9.8_5	20 to 60
Corning Advertisement[15]	Pyrex No. 7740	3.3		0 to 300

Note.—Value of linear expansion coefficient was found to vary from 3.07 to 3.42, dependent on temperature of heat treatment. Generally speaking, lower values result from a lower heat treatment.

* The specific type of Pyrex glass is indicated where known. The laboratory number 702EJ was assigned by the Corning Glass Works to the early form of glass now known as "Pyrex". This glass was sold under the code number 774. Various changes in raw materials, but no substantial alteration of final composition, have resulted in changes in the laboratory designation until it now stands at 726MX. The marketing code was kept at 774 until the large number of compositions being made necessitated a fourth digit and 774 became 7740.[5] Perhaps the chief alteration in the composition of this "Pyrex" glass was the reduction of As_2O_3 content from 0.40 per cent to about 0.00002 per cent, announced in 1936.[16]

different from those used in any previously reported investigation and that the temperature range is much smaller than any previously reported.

EARLIER EXPERIMENTS ON EXPANSIVITY

Approximately 18 months before the work described in the preceding sections, exploratory experiments were conducted in order to become acquainted with the apparatus, to acquire manipulative technique, and to obtain an indication of the magnitude of the expansion of the floats.

Two of the floats, Nos. 2 and 3, survived this early work and were also used in the experiments of the previous section. The other float, No. V-1, was broken during later handling and was not available for further study. This float, No. V-1, was evacuated during fabrication. After the initial determination on Float No. V-1, it was carefully ground on emery paper and redesignated Float No. V-1a.

The water used for these preliminary experiments was taken directly from the distilled water tap without further treatment. It was assumed that this water was air-saturated. At each new temperature setting, the water in the float chamber was agitated and the float repositioned approximately one cm. from the bottom of the float chamber.

The density of air-saturated water is less than that of air-free water at the

[12] "International Critical Tables," McGraw-Hill Book Co., New York, 1928, Vol. II, p. 93.

[13] R. M. Buffington and W. M. Latimer, *J. Am. Chem. Soc.*, **48**, 2312 (1926).

[14] G. Jones and F. C. Jelen, *ibid.*, **57**, 2532–2536 (1935).

[15] Anon., *Chem. Eng. News*, **31**, 4709 (1953).

[16] W. C. Taylor, *Ind. Eng. Chem., News Ed.*, **14**, 23 (1936).

same temperature. Marek's values for the difference in specific weight, d', of air-saturated water and, d, of air-free water at one atm.[17] were used to correct for this difference.

The results of these preliminary experiments ranged from 9.9_2 to $11.6_4 \times 10^{-6}$ per deg. and have been reported in another publication.[18] The average value of these preliminary determinations, $10.8_7 \pm 0.7_3 \times 10^{-6}$, is approximately one part per million greater than the average value of aged micro-floats, $9.8_6 \pm 0.1_3 \times 10^{-6}$, from Table 3.

One would naturally question the validity of these preliminary results because duplicate determinations were not made to check the various values. At the time of measurement, the magnitude of these values was not questioned because the individual float velocity determinations were consistent with the calculated values of flotation temperatures.

The biggest difference in experimental methods lies in the fact that for the preliminary experiments it was assumed that the water was air-saturated whereas in the experiments reported in Tables 1, 2 and 3, steps were taken to insure air-free conditions. Two different corrections were applied to tabulated density values for these two different cases.

Another difference in the two experimental methods lies in the fact that during the preliminary experiments resistance values for the platinum thermometer were recorded only to the fourth decimal place, whereas in the later experiments estimates were made to the fifth decimal place. An analysis of the experimental procedure indicates that the probable error in the coefficient of expansion for the preliminary technique with air-saturated water was about $\pm 1.0 \times 10^{-6}$. However, for the air-free measurements reported in Tables 1, 2 and 3, the probable error is only $\pm 0.1 \times 10^{-6}$.

One other comment should be made regarding a comparison of the preliminary results with those in Table 3. Richards and Harris noted a significant contraction in volume of floats with time over intervals of 34 to 73 days.[19] The preliminary values were obtained on floats within a week after their manufacture. Approximately 18 months elapsed before making the measurements reported in Table 3. It would be reasonable to assume that this contraction in volume on ageing is similar to the contraction which is observed on annealing. It would then be expected that there would be a decrease in the coefficient of expansion for a float which has aged for a period of time. This hypothesis could be checked by making careful determinations of the coefficient of expansion over an extended period of time.

ACKNOWLEDGMENT

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[17] W. J. Marek, *Ann. d. Physik (Wied.)*, **44**, 171–2 (1891); cited by Dorsey, Table 92, p. 198.

[18] M. Dole, *Chem. Rev.*, **51**, 266 (1952).

[19] T. W. Richards and G. W. Harris, *J. Am. Chem. Soc.*, **38**, 1000 (1916).

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